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Determining onboard capacity for the initial skill training

Lawphongpanich, Siriphong.

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Determining Onboard Capacity for Initial Skill Training

by

Siriphong Lawphongpanich

November 2000

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NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5000

RADM David R. Ellison
Superintendent

Richard Elster
Provost

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This report was prepared by:

[redacted]

Siriphong Lawphongpanich
Assoc. Professor of Operations Research

Reviewed by:

[redacted]

R. Kevin Wood
Associate Chairman for Research
Department of Operations Research

[redacted]

James N. Eagle
Chairman
Department of Operations Research

Released by:

[redacted]

David W. Netzer
Associate Provost and
Dean of Research

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In an effort to provide quality training and education to its personnel in the most effective and efficient manner, the Navy must continue to monitor and evaluate its training and education programs and their operations. One critical factor in a successful operation of a training site is its onboard capacity. Insufficient onboard capacity would delay training or produce insufficient number of trained sailors for the fleet. This report describes two related optimization problems whose solutions are useful in determining an appropriate onboard capacity, setting training quota, and evaluating the effectiveness of convening schedules. Data from the Service School Command at Great Lakes, Illinois are used to illustrate these applications.

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Determining Onboard Capacity for Initial Skill Training

Final Report

Siriphong Lawphongpanich

Operations Research Department

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Prepared for
Deputy Chief of Naval Operations
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ABSTRACT

In an effort to provide quality training and education to its personnel in the most effective and efficient manner, the Navy must continue to monitor and evaluate its training and education programs and their operations. One critical factor in a successful operation of a training site is its onboard capacity. Insufficient onboard capacity would delay training or produce insufficient number of trained sailors for the fleet. This report describes two related optimization problems whose solutions are useful in determining an appropriate onboard capacity, setting training quota, and evaluating the effectiveness of convening schedules. Data from the Service School Command at Great Lakes, Illinois are used to illustrate these applications.

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1. INTRODUCTION

The Navy must recruit new sailors on a regular basis to replace those who leave the service, by choice or otherwise. Generally, new recruits have no prior enlistment experience and must undergo basic training at the recruit training center (RTC) at Great Lakes, Illinois. After completing basic training, recruits become sailors and they are referred to herein as 'student sailors' in order to distinguish them from those already in the fleet. Student sailors continue their pre-fleet training by taking general apprentice training courses such as those in the Seamen and Airmen Apprentice Schools and some take 'initial skill training' (or 'A' school) courses to develop skills for specific jobs in the fleet. For many, their pre-fleet training ends after 'A' school. However, some student sailors also take 'skill progression training' (or 'C' school) courses prior to joining the fleet.

For the enlisted alone, the Navy operates and manages more than 3,000 courses over 100 training sites located throughout United States. Data from the Navy Training Management and Planning System (NTMPS) also indicate that a course may convene up to 344 times annually. In general, the number of convenings for each course depends, among other factors, on its yearly demand and class size. While in training, most, if not all, recruits and student sailors live on base and there must be sufficient berthing and messing facility for them. One major concern is whether a training site has sufficient facilities or *onboard capacity* to train recruits or student sailors in the quantity and manner required by the fleet.

This report addresses enlisted training and focuses on the onboard capacity at a given training site. In particular, the report describes two related optimization problems whose solutions are useful, e.g., in determining an appropriate onboard capacity for a training site, estimating training time, and setting training quotas. Section 2 describes the enlisted training process, the operation at the Service School Command at Great Lakes, Illinois, and a classification of time not under instruction. Section 3 states the two optimization problems and discusses their underlying network structure. Finally, Sections 4 provides several applications and Section 5 concludes the report.

2. BACKGROUND

This section provides the necessary background for the optimization problems described in Section 3. The first subsection describes elements of the enlisted training process and the second supplies information regarding the Service School Command, a training site at Great Lakes, Illinois. The last section provides information regarding the time student sailors accumulated while not under instruction which is one measure of training efficiency.

2.1 Enlisted Training Process

To maintain a sufficient level of enlisted strength, the Navy must replacement those sailors who leave the service annually. Navy Recruiting Command (NRC) has been focusing on the population of 17 to 21 years old individuals as potential recruits for the fleet. Typically, these individuals have no prior enlistment experience and NRC separates them into two groups. One group, called the 'high school market', consists of individuals who are still in high school. These individuals (students) sign enlistment contracts while in high school and agree to undergo basic training after graduation. While in school and waiting for basic training, recruits must join the Delayed Entry Program or DEP. (See Figure 2.1-1.) Recruits may remain in the DEP up to twelve months depending on their graduation dates, capacity of the RTC, and availability of follow-on training courses at the apprentice, 'A', and 'C' schools. The other group, called the 'workforce market', includes individuals who are no longer in high school and may already have a job. Some of these individuals graduated from high school, some have General Equivalency Diplomas or GED, and the rest has neither. Workforce recruits either enter basic training immediately upon signing the enlistment contract or join the DEP for up to three months.

After closing the RTCs in Orlando, Florida and San Diego, California, the Navy now operates only one training center at Great Lakes, Illinois. The RTC at Great Lakes consists of 14 barracks. Each barrack has 12 divisions and each division holds approximately 90 recruits. Basic training at RTC lasts 9 weeks and a new training class begins as soon as there are enough recruits to form a division. Typically, there is a new

division formed every day. Prior to the 9-week training program, recruits lacking basic skills are required to undergo additional training. On average, 4% and 1% of recruits take the Fundamental Applied Skills Training (FAST) and Personal Applied Skills Streaming (PASS) course, respectively, in addition to basic training.

FAST started in the early 1980s (see, e.g., Quester et al [1998]) and is designed to give recruits with low reading comprehension or insufficient language skills a better chance of completing basic training. PASS began in May 1997 and focuses on improving recruits' interpersonal skills. Ross [1998] estimated that the average training time at RTC is approximately 71 days when FAST and PASS are taken into account.

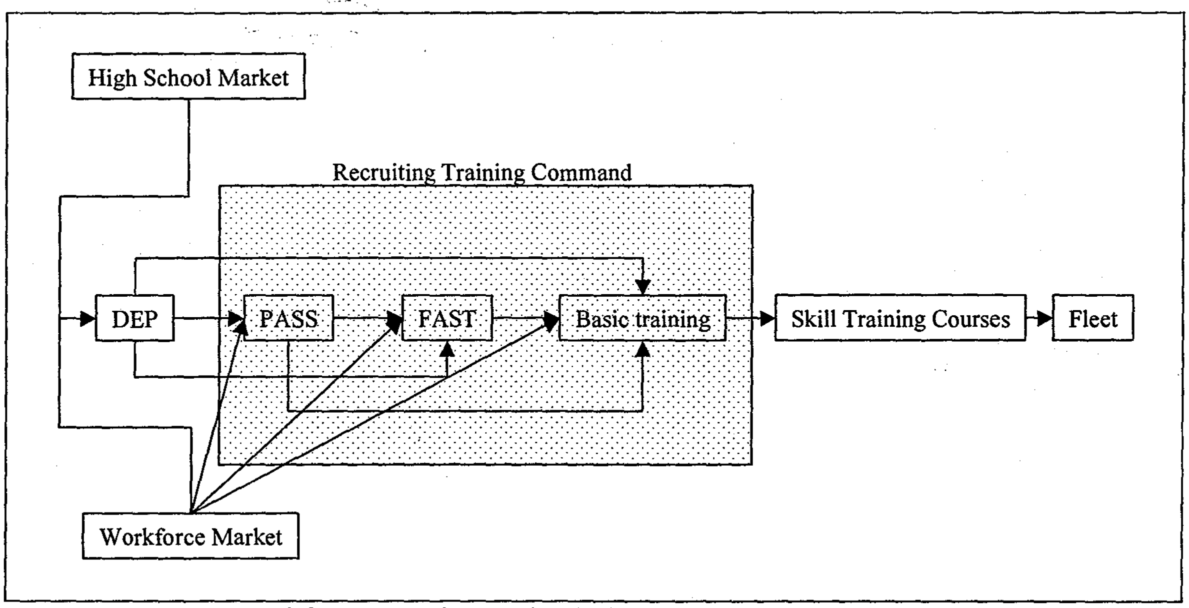

Figure 2.1-1: A workforce recruit may begin basic training at the Recruit Training Command immediately after signing an enlistment contract or wait in the Delayed Entry Program (DEP) for a more convenient time to begin training. Recruits lacking basic skills are required to take the Personal Applied Skills Streaming or Fundamental Applied Skills Training course or both prior to basic training. After completing basic training and prior to joining the fleet, recruits become student sailors and undergo skill training at various training commands located throughout United States. High school recruits follow a similar training path. Because these recruits are still in school upon signing the contract, they must remain in the DEP at least until graduation.

After basic training, recruits become student sailors and take initial training courses at one or more of the 100 training sites located throughout United States. For the GENDET community, student sailors with SN (Seaman), AN (Airman), and FN (Fireman) designations take, respectively, the Seaman, Airman, and Fireman Apprentice

Training course prior to joining the fleet. Student sailors with Seaman-Submarine designation take the Seaman-Submarine Apprentice Training course and attend the Basic Enlisted Submarine School instead.

For other enlisted communities, student sailors may take one or more 'initial skill training' or 'A' school courses. Figure 2.1-2, taken from Sladyk [1999], displays the initial skill training courses for recruits in the Combat Community. Student sailors with low aptitude must also undergo Job Oriented Basic Skills (JOBS) training prior to 'A' school. As described in Main et al [1989], JOBS provides low aptitude recruits with basic or prerequisite skill training needed to complete selected 'A' school courses. JOBS program covers training areas (or strands) such as propulsion engineering, operations, electricity, and electronics.

When two or more 'A' school courses are required, they are taken one at a time in a predetermined order. A sequence of two or more courses is referred to as a 'pipeline'. In Figure 2.1-2, the pipeline for Electronic Technician [Communication] rating consists of two courses, 'AETC Common Core' with course data processing (CDP) code 622L and 'ET-Strand' with CDP 2444.

Student sailors generally join the fleet after having completed the required 'A' school courses. However, FY 1997 and FY 1998 data from the Navy Integrated Training Resources Administration System (NITRAS) show that approximately 26% of these student sailors also take 'skill progression training' or 'C' school courses before joining the fleet. Information from the Street-To-Fleet database (see, MacIlvaine [1998]) indicates that the average training time for these student sailors is approximately 21 months.

The 'A' and 'C' school courses are grouped according to the enlisted community they serve. Courses for the same community are usually offered at the same training site. The next subsection describes the Service School Command at Great Lakes, Illinois.

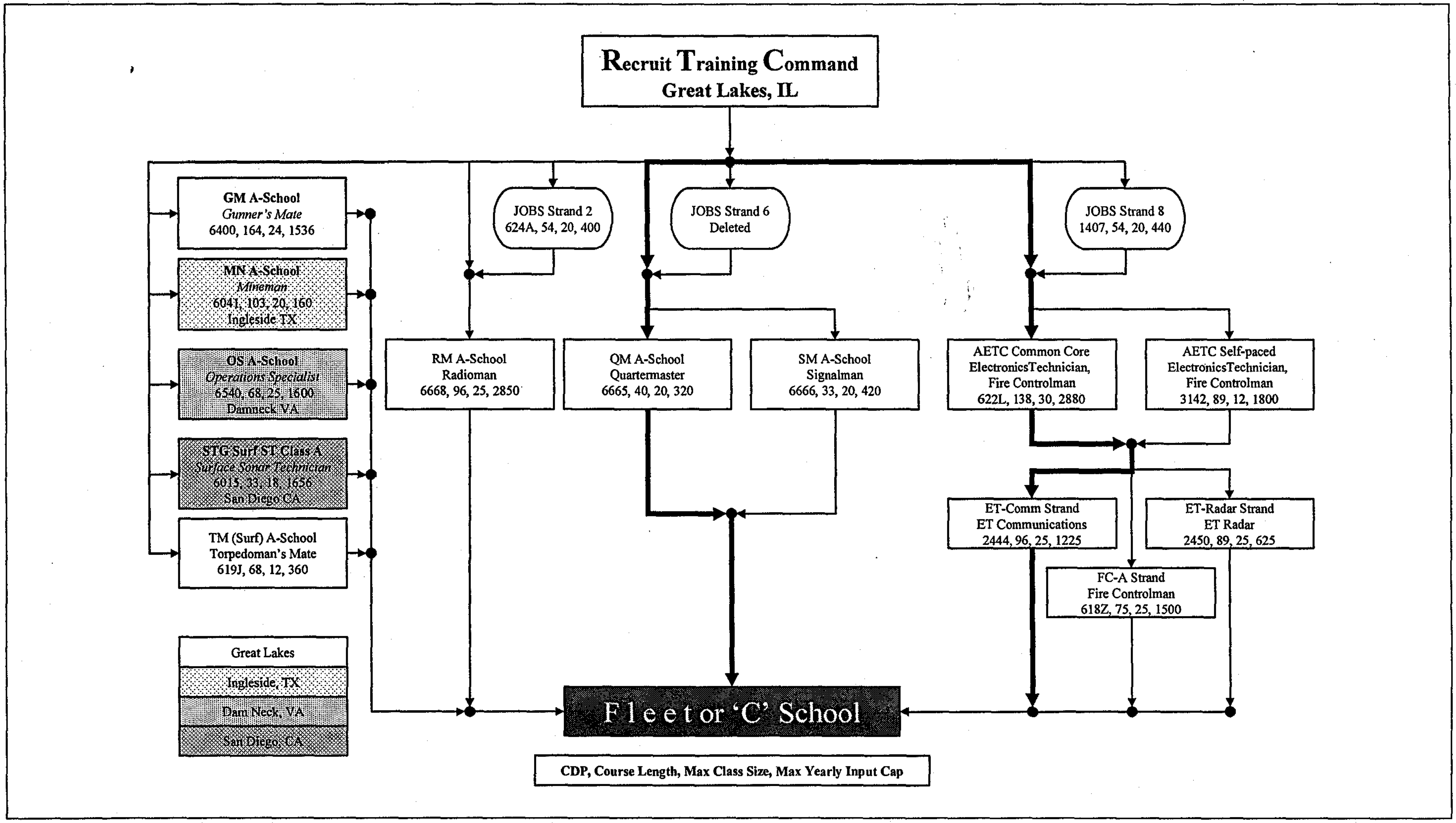

Figure 2.1-2: Student sailors in the Combat Community takes one or more 'A' school courses after basic training. The requirement varies depending on the sailor's rating. For example, the Quartermaster (QM) rating requires only one course–the QM 'A' School–and the Electronic Technician-Communication (ET-C) rating requires two, AETC Common Core and ET–Comm Strand. Student sailors with deficient educational background must take a Job Oriented Basic Skills (JOBS) Training course in addition to 'A' school courses. Courses in unshaded boxes are taught at the Service School Commands at Great Lakes and those in shaded boxes are offered elsewhere as indicated.

2.2 Service School Command at Great Lakes

The Service School Command (SSC) at Great Lakes offers 122 separate courses and provides approximately 70% of the Surface Navy's initial skill training. Included in this 70% are the 'A' school courses in the training pipelines (see, e.g., Sladyk[1999]) listed in Table 2.2-1.

Rating	Description	Course 1	Course 2	Course 3	Course 4
GENDET(AN)	Airman Apprentice	621V			
DC	Damage Controlman	617V	621N		
EM	Electrician's Mate	617V	618J	6070	
EN	Engineman	617V	618N	6741	
ET(Comm)	Electronic Technician (Communication)	622L	2444		
ET(Radar)	Electronic Technician (Radar)	622L	2450		
FC	Fire Controlman	622L	618Z		
GENDET(FN)	Fireman Apprentice	617V			
GM	Gunner's mate	6400			
GSE-pipe 1	Gas Turbine System Technician (Electrical)	617V	618N	6609	618J
GSE-pipe 2	Gas Turbine System Technician (Electrical)	617V	618J		
GSM	Gas Turbine System Technician (Mechanical)	617V	618N	6609	
HT	Hull Maintenance Technician	617V	6662		
IC	Interior Communications Electrician	617V	618J	619G	
MM	Machinist Mate	617V	618N	6611	
MR	Machinery Repairman	617V	621S		
QM	Quartermaster	6665			
RM	Radioman	6668			
SM	Signalman	6666			
GENDET(SN)	Seaman Apprentice	621L			
TM	Torpedoman's mate	619J			

Table 2.2-1: Initial skill training pipelines at the Service School Command at Great Lakes, Illinois.

According to its homepage, SSC has sufficient infrastructure to support up to 7,000 students on board at any one time and data from NTMPS indicate that averages of students on board (AOB) from FY 1997 to FY 1999 are 6254.83, 6600.65, and 5964.32, respectively. (For other information, see Funke [1998].) These numbers include both student sailors and sailors from the fleet who are in specialized skill training at SSC. (Sailors in the latter group are also referred to as 'fleet returnees' in, e.g., Belcher [1999] and by Ross [1998].) Table 2.2-2 lists the AOB for each course in Table 2.2-1.

Summing these AOBs gives an estimate of the total number of student sailors on board at SSC. These estimates are 4967.90, 5751.17, and 5116.50 for FY 1997, FY 1998, and FY 1999, respectively. Based on the two sets of numbers, approximately 84%[1] of sailors undergoing training at SSC are student sailors. Note that the 84% estimate does not account for those sailors who took 'C' school courses in addition to the 'A' school.

CDP	Description	FY 1997	FY 1998	FY 1999
2444	ET COMM STRAND	139.07	421.38	473.78
2450	ET RADAR STRAND	64.25	300.97	230.02
6070	ELECT MATE A	83.32	55.26	66.66
617V	ENG CORE	442.82	363.83	325.02
618J	ELEC CORE	388.01	301.03	324.60
618N	MECH CORE	148.72	158.70	150.99
618Z	FC A STRAND	246.66	386.91	369.31
619G	IC A	76.35	46.68	56.13
619J	TM 'A'	14.79	28.86	31.30
621L	SA TRAINING	220.81	284.25	255.18
621N	DC A	20.43	51.64	83.78
621S	MR A	26.90	19.66	18.42
621V	AA TRAINING	236.06	385.61	250.63
622L	AETC	1669.11	1708.91	1174.19
6400	GM A	254.79	240.48	267.98
6609	GSM/E 'A' SCHOOL	215.44	102.21	88.16
6611	MM CLASS A 4YO	69.65	79.51	84.88
6662	HT A	70.19	42.41	49.62
6665	QM A	18.81	35.28	37.58
6666	SM A	32.95	16.75	33.59
6668	RM A	364.92	587.17	619.33
6741	ENGINEMAN A	163.85	133.67	125.35
Total		4967.90	5751.17	5116.50

Table 2.2-2: The last three columns give averages of students taking each course on a given day during the last three fiscal years. The last row gives the sums of these averages and they are estimates of the average number of student sailors on board at the Service School Command at Great Lakes, Illinois.

2.3 Time Not Under Instruction

Student sailors on board at training sites are not always under instruction. Student sailors not under instruction (NUI) may be waiting for orders to leave the training site, having their training interrupted for, e.g., medical reasons, or waiting for a course to convene. The time student sailors spent in NUI status regularly monitored by the training

[1] $0.84 \approx (4967.90 + 5751.17 + 5116.50) \div (6254.83 + 6600.65 + 5964.32)$.

sites, for it delays student sailors from joining the fleet and prevents other from receiving training by taking up onboard capacity and, perhaps, training seat as well. Belcher et al [1999] reports that student sailors accumulated over 4,000 man-year of NUI time annually during fiscal years 1997 and 1998. Using an average cost of $25,000 per man-year, this translates into an annual cost of over $100 million.

NUI time has three components and they include interrupted-instruction (II) time, awaiting-transfer (AT) time, and awaiting-instruction (AI) time. The II time represents the time that students have to interrupt their training for medical, legal, administrative, and other reasons. During stand-down (or holiday) period at the end of the year, some student sailors take leave and some stay at school or remain in the area. In addition to the above categories, the II time also includes students' time during this stand-down period regardless of their holiday decision. According Belcher et al [1999], the II time varied between 600 and 750 man-years (or approximately 5% of the total training time) during each of the last four fiscal years. Approximately 50% of the II time is due to the stand-down period. For the remaining categories (medical, legal, administrative, and other reasons), each accounts for at most 20%.

The AT time represents the time that students have to wait before he or she can leave the training site. NITRAS separates AT time into four primary categories and they include student sailors waiting to be transferred for legal, medical, administrative, and other reasons. Belcher et al [1999] further separates the administrative category into four subcategories as follows:

1. Waiting for orders
2. Waiting for transfer dates after having received orders
3. Waiting for separation or discharge orders
4. Others.

During FY 1997, there were 1,079 man-years of AT time. Approximately 25% and 20% of which were classified as waiting for orders and transfer dates, respectively.

The AI time represents the time that students have to wait for instruction at a training site. NITRAS classifies AI time as follows:

1. **On board prior to convening**: This (primary) category assumes that there is a sufficient number of training seats available and represents the AI time accumulated by students who have to wait for a course to convene under the following subcategories:

    a) Early: The AI time in this subcategory is from students in the following groups:

        i) Initial Arrival: Students who arrive at the training site prior to the start of their first course in the pipeline.

        ii) Setback: Students who start instruction in one course convening and are reassigned to a later one in order to repeat the portion of the course that they have not adequately mastered or missed for academic or nonacademic reasons.

        iii) Between Courses: Students who have to wait for a course to begin after having completed a prerequisite course in a course pipeline.

    b) Backlog: The AI time accumulated by students who have to wait for instructions due unavailable training seats. Training seats may become unavailable when students arrive a training site because

        i) Excessive student input: In this case, the number of students arriving at a training site is more than the number of available training seats (or quotas) due to overbooking or overselling of quotas for a rating or enlistment program.

        ii) Constrained capacity: The planned course capacity was reduced because of insufficient number of instructors, equipment, or space.

2. **Hold Preventing Enrollment**: This (primary) category represents the AI time accumulated by students who are prevented from enrolling in a course for medical, legal, administrative, and other reasons.

Of the approximately 1,950 man-years of AI time in FY 1997 (see Belcher et al [1999]), approximately 1,750 man-years were from the 'on board prior to convening' category. Within this first primary category, the AI times for the 'initial arrival' and 'between courses' group were 1,279 and 155 man-years, respectively.

One of the optimization problems in the next section directly addresses the 'between courses' AI time. The other categories or subcategories of AI times can be accounted for indirectly when determining onboard capacity for a training site.

3. DETERMINING ONBOARD CAPACITY FOR INITIAL SKILL TRAINING

This section describes two related optimization problems that are useful in determining an onboard capacity for initial skill training (or 'A' school capacity), one is the 'maximum output' (or Max-Out) problem and the other is the 'minimum AI time' (or Min-AI) problem. To make the problems tractable and more amenable for analysis, the first subsection lists the necessary assumptions. The second subsection describes the underlying network structure common to both problems. The third and fourth subsections provide mathematical formulations for the two problems.

3.1 Assumptions

Below are two assumptions for the Max-Out and Min-AI problems.

1. When a student fails to complete a course for, e.g., academic, administrative, or medical reasons, several events can occur. First, the student may repeat the same course one or more times and, each time, the student may either repeat the entire course or parts of it. Second, the student may be assigned a new and, perhaps, less demanding rating and has to take a different course. Finally, the student leaves the training site to join the fleet, take courses at a different training site, or leave the Navy. Because the data on these students are not readily and accurately available, both Max-Out and Min-AI problems assume that the graduation rate for every course is 100%. This assumption also makes the resulting problems more tractable and easier to solve. (Section 4 illustrates to accommodate this assumption when estimating the onboard capacity at SSC.)
2. Both Max-Out and Min-AI problems assume that every student arrives at the start of the first course and leave the training site at the end of the last course in his or her course pipeline. Therefore, there is no AT or Initial Arrival AI time.

3.2 Network Structure

Associated with each course pipeline, there is a collection of training paths. These training paths consist of exactly the same sequence of courses, but at different convening dates. Moreover, training paths for the same pipeline may be of different length and accumulate different 'between courses' AI time. The former is because the length of a

course varies depending on its convening date and the latter is due to the fact that the 'between course' AI time may be different with different convening dates

One method for modeling all possible training paths is via a network of nodes and arcs. A node in this network corresponds to a course convening and an arc between two nodes indicates that one course convening can follow the other in a training path. To illustrate, consider a fictitious training site that offers three training courses: A, B, and C. Table 3.2-1 provides the necessary information for each of the three courses.

Course	**Class Size**	**Duration (days)**	**Convening Dates**
A	35	5	1, 8, 15, 22, 29
B	25	10	1, 14
C	20	3	4, 11, 17, 23

Table 3.2-1: Course information at a fictitious training site.

Student sailors trained at this site are assigned either a R1 or R2 rating. Rating R1 requires a pipeline consisting of course A followed by course C. Similarly, the pipeline for R2 consists of course B followed by course A.

Figure 3.2-1 displays a network representation of all possible training paths for rating R1. In the figure, nodes A1 to A5 and C1 to C4 denote the five convening dates for course A and four convening dates for course C, respectively. Node *s* and *t* represent the beginning and the end of the scheduling process. If it is possible to take the i^{th} convening of course A and the j^{th} convening of course C in sequence, then there is an arc from node A*i* to node C*j* with an associated 'between courses' AI time, if any. For example, there is an arc from node A1 to C2 because it is possible to take course A at its first convening that starts on day 1 and ends on day 6, wait 5 days, and take course C at its second convening that starts on day 11. In this case, the associated 'between courses' AI time for arc from node A1 to node C2, denoted as (A1, C2), is 5 days. On the other hand, there is no arc between node A3 and node C3 because the third convening for course A ends on day 20, three days too late for the third convening for course C that begins on day 17.

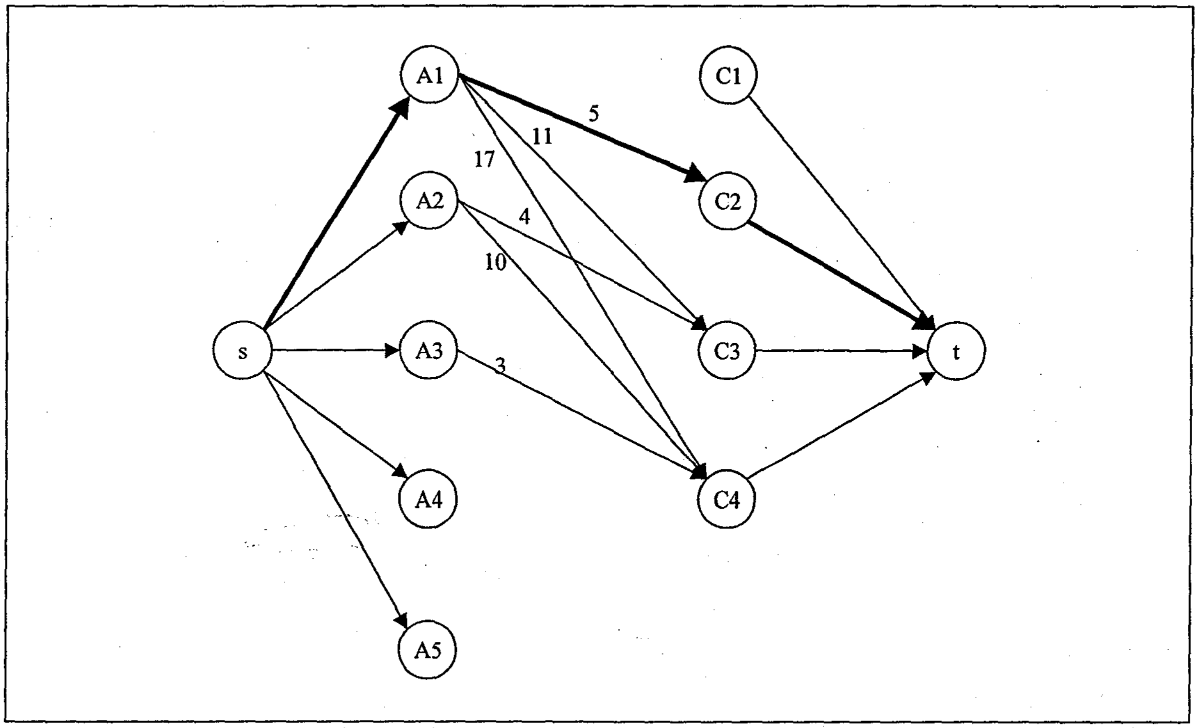

Figure 3.2-1: All possible training paths for rating R1 can be represented as a network in which nodes A1 to A5 and C1 to C4 denote the five convening dates for course A and four convening dates for course C, respectively. Node *s* and *t* represent the start and finish of the scheduling process. As an example, the path *s* – A1 – C2 – *t* corresponds to taking course A at its first convening that starts on day 1 and ends on day 6, waiting 5 days, and taking course C at its second convening that starts on day 11.

Arcs from node *s* to node A*i*, for *i* = 1,...,5, indicates that it may be possible to begin training for rating R1 by taking course A at any one of the five convening dates. Similarly, arcs from C*j*, for *j* = 1,...4, to node *t* signify that taking course C at any of its four convening dates may complete the required training for rating R1.

A path *s* – A1 – C2 – *t* represents taking the first convening for course A and the second convening for course C. The AI time associated with this training path is 5 days. Then, training 50 student sailors for rating R1 corresponds to sending 50 units of flow from node *s* to node *t* along the arcs (or paths) in the network in manner that minimizes the total AI time of the 50 students.

Similarly, all training paths for rating R2 can be represented as the network shown in Figure 3.2-2.

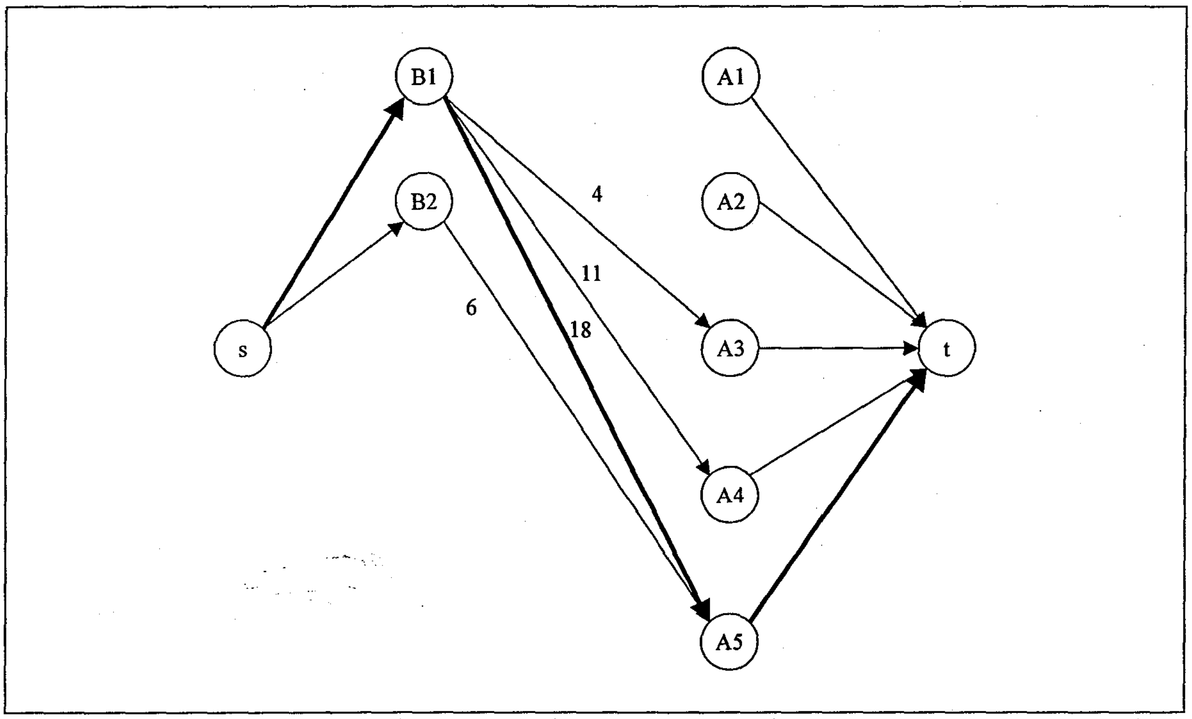

Figure 3.2-2: All possible training paths for rating R2 can be represented as a network in which nodes A1 to A5 and B1 to B2 denote the five convening dates for course A and two convening dates for course B, respectively. Node *s* and *t* represent the start and finish of the scheduling process. As an example, the path *s* – B1 – A5 – *t* corresponds to taking course B at its first convening that starts on day 1 and ends on day 11, waiting 18 days, and taking course A at its fifth convening that starts on day 29.

To illustrate, assume that the training site has an initial skill training capacity of 70 students. Then, Table 3.2-2 provides a feasible training schedule for the 90 student sailors with a resulting 'between courses' AI time of 400 days. The corresponding course utilization in Table 3.2-3 confirms that the number of student sailors assigned to each course convening is within its class size. In addition, the table also indicates that the fourth convening for course A and the first for course C may be cancelled or allocated to students from other services or foreign countries.

Rating	Path	Recruits	AI Time
R1	s – A1 – C2 – t	20	$5 \times 20 = 100$
	s – A2 – C3 – t	20	$4 \times 20 = 80$
	s – A3 – C4 – t	10	$3 \times 10 = 30$
R2	s – B1 – A3 – t	25	$4 \times 25 = 100$
	s – B2 – A5 – t	15	$6 \times 15 = 90$

Table 3.2-2: Paths for training 90 student sailors with a total AI time of 400 days

Data from Table 3.2-3 are also useful for examining the onboard profile due to the three training courses. When combined with the start and end dates of each course convening in Table 3.2-1, the paths in Table 3.2-2 and data from Table 3.2-3 produce the onboard profile shown in Table 3.2-4. On days 17, 18, and 19, the table shows that the number of student sailors on board reaches the capacity of 70 students.

		Convening				
Course	**Class Size**	**1**	**2**	**3**	**4**	**5**
A	35	20	20	35	0	15
B	25	25	15	–	–	–
C	20	0	20	20	10	–

Table 3.2-3: The course utilization based of the training paths in Table 3.2-2.

The above example shows that it is possible to train 50 student sailors for rating R1 and 40 for rating R2 at a training site with an initial skill training capacity of 70. The training schedule used for illustration yields a total 'between courses' AI time of 400 days. The following two subsections describe two optimization problems. One maximizes the number of student sailors that can be trained for a given capacity and the other minimize the amount of 'between courses' AI time accumulated by student sailors while in training.

Day	Course A	Course B	Course C	Total
1	20	25		45
2	20	25		45
3	20	25		45
4	20	25		45
5	20	25		45
6		25		25
7		25		25
8	20	25		45
9	20	25		45
10	20	25		45
11	20		20	40
12	20		20	40
13			20	20
14		15		15
15	35	15		50
16	35	15		50
17	**35**	**15**	**20**	**70**
18	**35**	**15**	**20**	**70**
19	**35**	**15**	**20**	**70**
20		15		15
21		15		15
22		15		15
23		15	10	25
24			10	10
25			10	10
26				0
27				0
28				0
29	15			15
30	15			15
31	15			15
32	15			15
33	15			15
34				0
35				0
Average on board	12.86	11.43	4.29	28.57

Table 3.2-4: The number of student sailors on board for each course at a fictitious training site. On days, 17, 18, and 19, the number of students on board reaches the capacity of 70 students. The last row in the table gives averages of student sailors on board over a 35-day period.

3.3 Maximum Output Problem

In the Max-Out problem, student sailors are assigned to training paths so as to maximize the number trained annually. There are two types of capacities that limit the number of students assigned to each training path. One is the capacity (or class size) of each course in the pipeline and the other is the capacity for initial skill training.

The Maximum Output or Max-Out problem assumes that an initial skill training capacity is given and determines how to assign student sailors to training paths in order to maximize the number trained annually.

Below is a formulation of the Max-Out problem.

Indices:	c, cp	a combination of convening date and training course or a (convening) date/course combination
	r	rating
	s	start of the scheduling process
	t	end of the scheduling process
	d	day in a fiscal year
Sets:	$\Omega(r)$	set of arcs, (c, cp), in the underlying network for rating r (For example, see Figure 3.2-1.)
	$\Delta(d)$	set of date/course combination that starts on or before day d
	$\Phi(d)$	set of date/course combination that ends on or before day d
Data:	cap_c	size of the date/course combination c
	req_r	requirement for rating r
	$ocap$	onboard capacity

Nonnegative Variables:

	$X_{r,c,cp}$	number of student sailors in rating r who take date/course combination c followed by date/course combination cp.

The Maximum Output (or Max-Out) Problem

Maximize $$\sum_{r}\left(\sum_{(c,t)\in\Omega(r)} X_{r,c,t}\right)$$

Subject to:

$$\sum_{(c,t)\in\Omega(r)} X_{r,c,t} \le req_r, \quad \forall r \tag{1}$$

$$\sum_{(c,cp)\in\Omega(r)} X_{r,c,cp} = \sum_{(cp,c)\in\Omega(r)} X_{r,cp,c}, \quad \forall r,c \tag{2}$$

$$\sum_{r}\sum_{(cp,c)\in\Omega(r)} X_{r,cp,c} \le cap_c, \quad \forall c \tag{3}$$

$$\sum_{r}\left[\sum_{(s,c)\in\Omega(r)\&c\in\Delta(d)} X_{r,s,c} - \sum_{(c,t)\in\Omega(r)\&c\in\Phi(d)} X_{r,c,t}\right] \le ocap, \quad \forall d \tag{4}$$

In the objective function, the inner summation is an expression for the number of graduates for rating *r*. Thus, summing over *r* in the outer summation gives the total number of graduates to be maximized. As in the objective function, the left hand side of equation (1) is the number of graduates for rating *r*. This number is constrained to be no greater than the number required so that onboard capacity not used by rating *r* can be diverted to train sailors for other ratings.

The summation on the right hand side of equation (2) is the number of student sailors who enrolled in course *c* and the one on the left is the number of graduates. To obtain an estimate of the capacity, the graduation rate is assumed to be 100% and the two sides of equation (2) must equal each other.

Constraints in equations (3) and (4) limit the number of student sailors in each course and on board to be within the respective capacities. The left hand side of equation (3) is the expression for the number of student sailors taking a course that corresponds to the date/course combination *c* and this number must be less than $ccap_c$, the course capacity. Of the two summations enclosed by the brackets in equation (4), the first one represents student sailors in rating *r* who start their training on or before day *d*. Similarly, the second represents the number of those who completed their training on or before day *d*. Thus, the difference between the two sums gives the number for those who are still on

board on day d and this number is limited by the onboard capacity at the training site denoted as *ocap*.

3.4 Minimum AI Time Problem

As an alternative to the Max-Out problem, the Minimum AI time or Min-AI problem assigns student sailors to training paths in order to minimize the total 'between courses' AI time for a given onboard capacity and a set of training requirements, i.e., the number of sailors to be trained for each rating. If the onboard capacity is insufficient, then there is no feasible solution to the problem and a larger onboard capacity is required. When there is an excess onboard capacity, the Min-AI problem uses it to reduce AI time, when possible.

Below is a formulation of the Min-AI problem. With the exception of the additional data, the notation is the same as in the Max-Out problem.

Data:	w_r	weight or priority for rating r
	$ai_{r,c,cp}$	AI time between date/course combination c and cp
	$ngrad_r$	number of graduates for rating r

<u>The Minimum 'between courses' AI Time (or Min-AI) Problem</u>

Minimize
$$\sum_r w_r \left[\sum_{(c,cp)\in\Omega(r)} ai_{r,c,cp} X_{r,c,cp} \right]$$

Subject to:
$$\sum_{(c,t)\in\Omega(r)} X_{r,c,t} = ngrad_r, \quad \forall r \tag{5}$$

$$\sum_{(c,cp)\in\Omega(r)} X_{r,c,cp} = \sum_{(cp,c)\in\Omega(r)} X_{r,cp,c}, \quad \forall r,c \tag{6}$$

$$\sum_r \sum_{(cp,c)\in\Omega(r)} X_{r,cp,c} \le cap_c, \quad \forall c \tag{7}$$

$$\sum_r \left[\sum_{(s,c)\in\Omega(r)\&c\in\Delta(d)} X_{r,s,c} - \sum_{(c,t)\in\Omega(r)\&c\in\Phi(d)} X_{r,c,t} \right] \le ocap, \quad \forall d \tag{8}$$

The objective function of the Min-AI problem minimizes the weighted 'between courses' AI time. Constraints in equation (5) are similar to those in equation (1) and ensure that the desired number of student sailors complete the training for rating r. Under

the current problem setting, it is logical to set $ngrad_r = req_r$. However, a different value of $ngrad_r$ may be appropriate for other situations. The remaining constraints are the same as those in the Max-Out problem.

Because the length of a course at different convenings are different and may contain II time, it may be also of interest to minimize the weighted initial skill training time as measured by course lengths as well. To do so, replace the objective function of the Min-AI problem with following:

$$\text{Minimize} \qquad \sum_r w_r \left[\sum_{(c,t)\in\Omega(r)} finish_c X_{r,c,t} - \sum_{(s,c)\in\Omega(r)} start_c X_{r,s,c} \right].$$

In the above expression, $start_c$ and $finish_c$ denote the start and finish dates for date/course combination c. Similar to before, the difference between the two sums inside the brackets gives the total time to train the required number of student sailors for rating r. Note that this total includes the 'between courses' AI time and any stand-down period that is counted toward the II time. When $w_r = 1/ngrad_r$, the resulting objective minimizes the average training time.

4. RESULTS AND APPLICATIONS

The Max-Output and Min-AI problems were implemented in GAMS (see, Brook et al [1988]) and solved using the CPLEX 6.5 solver (see, ILOG [1999]). The subsections below describe the input data and illustrate possible applications for the two problems.

4.1 Input Data

Table 4.1-1 provides the student inputs and the pipeline for ratings with initial skill training at SSC.

Rating	SIP	Course 1	Course 2	Course 3	Course 4
GENDET (AN)	4363	621V			
DC	541	617V	621N		
EM	775	617V	618J	6070	
EN	898	617V	618N	6741	
ET (Comm)	1125	622L	2444		
ET (Radar)	750	622L	2450		
FC	1481	622L	618Z		
GENDET (FN)	2688	617V			
GM	735	6400			
GSE (pipe 1)	258	617V	618N	6609	618J
GSE (pipe 2)	111	617V	618J		
GSM	476	617V	618N	6609	
HT	510	617V	6662		
IC	654	617V	618J	619G	
MM	1152	617V	618N	6611	
MR	198	617V	621S		
QM	303	6665			
RM	2654	6668			
SM	408	6666			
GENDET (SN)	4363	621L			
TM	241	619J			
Total	**24684**				

Table 4.1-1: Course pipeline and student input (SIP) for each rating with initial skill training at the Service School Command, Great Lakes, Illinois.

The composition of each pipeline in Table 4.1-1 is based on information in Sladyk [1999] (see also Funke[1998]). The student input for each rating is adapted from Davidovich's FY 2000 student inputs (see Davidovich [1998]) and each one accounts for possible attrition and disenrollment.

This report uses FY 2000 course convening and graduation dates in NTMPS to construct the network of training paths described in the previous section. Table 4.1-2 summarizes the data from NTMPS. For each course, the number of convenings in the second column is slightly different from the 'course frequency' listed in the NTAS/GENTMPS Course Details Basic Data Report (or the Basic Data Report) in NTMPS.

CDP	Number of Convenings	Course Length Minimum	Average	Maximum	NTAS	Class Size
2444	60	94	104.66	120	96	25
2450	26	86	97.89	113	89	25
6070	31	23	28.60	45	26	25
617V	344	16	21.09	39	19	25
618J	70	81	87.30	102	81	25
618N	113	10	21.21	32	24	25
618Z	82	71	81.90	98	75	25
619G	38	35	37.03	55	36	20
619J	12	70	73.24	87	68	12
621L	124	11	13.01	17	12	40
621N	22	46	55.27	67	54	25
621S	6	77	84.00	95	75	24
621V	153	10	20.57	31	19	40
622L	74	134	147.38	165	141	30
6400	28	117	123.21	139	164	24
6609	29	45	54.19	69	56	25
6611	43	20	26.35	46	26	25
6662	37	46	52.32	67	54	14
6665	21	39	42.87	57	40	20
6666	14	32	33.89	35	33	20
6668	97	98	104.57	118	96	25
6741	48	58	62.07	81	73	25

Table 4.1-2: Summary information for courses at the Service School Command at Great Lakes, Illinois. Each course has many pairs of convening and graduation dates. Different pairs may be of different lengths because some pairs include weekends and holidays.

The column labeled 'NTAS' in Table 4.1-2 displays course lengths from the Basic Data Report. As an alternative, it is possible to compute (actual) course lengths from each pair of convening and graduation dates in NTMPS. The minimum, average, and maximum lengths for each course are displayed in the same table. Courses that convene during the first quarter of each fiscal year tend to be longer in length because of Thanksgiving, Christmas, and New Year. The difference between the maximum and the

NTAS lengths can be as long as 25 days, a significantly large number. Similarly, the difference between the minimum and maximum lengths can be as long as 31 days.

In solving the Max-Out and Min-AI problems, it is assumed that training paths with a gap of 30 days or longer between any pair of courses are disallowed. This reduces the number of arcs in the network of training paths and the number of variables in the optimization problems to those that can be solved using a personal computer with 256 MB of memory.

In addition, if a student sailor starts his or her training during a fiscal year, the student is counted as being trained during that year even though the student may not complete the training until the following fiscal year.

4.2 Applications

Optimal solutions to the Max-Out and Min-AI problems can be useful in determining an appropriate onboard capacity for a training site, quantify the effectiveness and efficiency of a convening schedule, and setting training quotas. Below, these applications are illustrated with data for the Service School Command at Great Lakes.

Determining onboard capacity: One method of determining an onboard capacity that produces a required number of trained sailors in a given year is to solve the Max-Out problem several times, each time with a different capacity. Figure 4.2-1 displays the number of trained sailors for an initial skill training capacity varying from 4500 to 7000 students. Two sets of convening and graduation dates were used as inputs to the Max-Out problem. One set is FY 2000 convening schedule described in Subsection 4.1 and the other assumes that there are two classes instead of one for each of the convening dates in FY 2000. This effectively doubles the capacity or number of training seats in each class and the number of convenings scheduled for FY 2000.

The second set of convening and graduation dates was introduced because the number of convenings in Table 4.1-2 is not sufficient to train the required number of sailors. Figure 4.2-1 indicates that FY 2000 schedule can only train 22,977 student sailors, approximately 93% of the required number. However, when the number of

convenings is doubled, the number that can be trained increases to 24,684, the required number in Table 4.1-1.

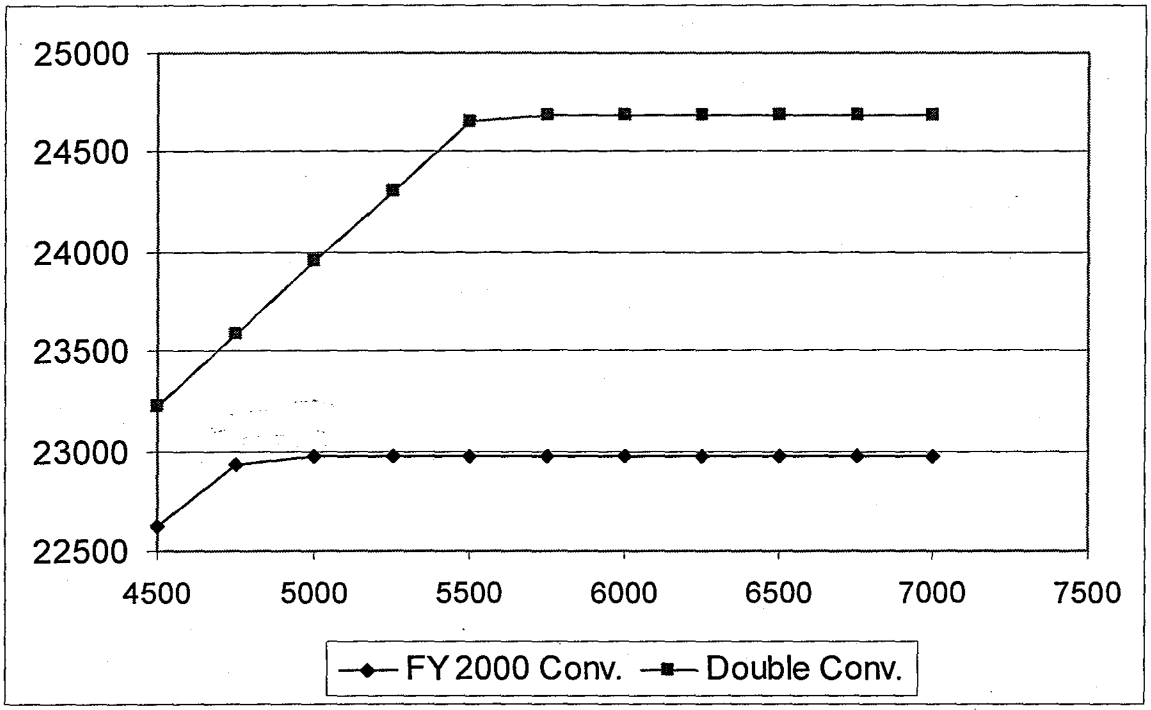

Figure 4.2-1: The number of student sailors that can be trained at the Service School Command with the initial skill training capacity varying from 4500 to 7000 students and two different sets of convening and graduation dates. One is from FY 2000 and the other has the same dates with twice the number of convenings.

The graphs in Figure 4.2-1 level off when the initial skill training capacity is a sufficiently large. For example, the number of graduates using FY 2000 schedule increases from 22,624 to 22,977 when the capacity increases from 4,500 to 5,000 students. For a capacity larger than 5,000[2], i.e., the 'breakpoint' capacity, the number of graduates remains constant at 22,977. The limiting factor in this case is the course capacities–some courses do not have sufficient capacities or training seats. When the number of FY 2000 convenings is doubled, the breakpoint is 5,750 and the maximum number of graduates increases to 24,684, the required number. This maximum is limited by the constraints in equation (1), for they prevent the number of trained sailors from

[2] In Figure 4.2-1, the Max-Out problem was solved with an onboard capacity varied from 4,500 to 7,000 students at an increment of 250. Using a smaller increment, it may be possible to find smaller breakpoints.

exceeding each rating's requirement. Removing equation (1) from the Max-Out problem would allow more to be trained with a larger onboard capacity as long as the courses have sufficient capacities to train the additional students on board.

The breakpoints in Figure 4.2-1 depend on the set of convening and graduation dates. However, the figure points out that FY 2000 schedule have insufficient number of convenings to produce the required number of trained sailors listed in Table 4.1-1. On the other hand, simply adding an extra class to each convening dates in FY 2000 schedule is not optimal. A better or a more 'optimal' set of convening dates may reduce the breakpoint capacity. (The 'between courses' AI time may also decrease.)

When a good or 'optimal' set of convening and graduation dates is available, the breakpoint capacity is useful in determining an onboard capacity at a training site. If there is no NUI time other than those inherent to the course schedule (i.e., the time due to 'between courses' AI and II due to weekends and holidays), then the breakpoint would be the minimum onboard capacity to train the required number of sailors. Otherwise, an additional onboard capacity is necessary to accommodate student sailors in various categories of NUI. To illustrate, Table 4.2-1 displays averages of students on board (AOB) under AI, AT and II statuses during the last three fiscal years. Adding the three totals (609, 279, and 295) to a breakpoint capacity provides a ballpark estimate for an onboard capacity for the initial skill training. Doing so yields an onboard capacity of 6,183 students for FY 2000 schedule and 6,933 students for the one with the number of FY 2000 convenings doubled.

To obtain an onbaord capacity for the SSC at Grate Lakes, an additional capacity must be planned for student sailors with 'C' schools in their course pipeline and sailors in specialized skill training (or fleet returnees). Recall that the AOB for student sailors is 84% of the total AOB at SSC. So, dividing the two estimates by 0.84 gives the desired onboard capacity with respect to each convening schedule. For FY 2000 schedule, the capacity is 7,361 students and it is 8,254 students when we double the number of FY 2000 convenings.

CDP	AI	II	AT
2444	21.04	21.62	46.15
2450	11.96	11.76	37.70
6070	7.69	3.08	12.32
617V	43.26	15.95	11.96
618J	36.24	18.72	15.86
618N	20.36	9.12	0.52
618Z	11.50	16.81	18.35
619G	6.16	1.80	8.42
619J	4.80	1.29	1.17
621L	42.92	2.40	18.72
621N	11.74	2.43	2.49
621S	3.40	1.36	0.33
621V	41.63	1.27	13.14
622L	217.94	104.95	6.61
6400	24.55	14.15	13.89
6609	22.86	6.67	14.64
6611	6.51	4.26	8.51
6662	5.58	3.64	2.90
6665	5.59	0.65	2.07
6666	6.00	1.16	2.05
6668	47.48	28.87	47.42
6741	9.45	7.04	9.93
Total	608.67	279.03	295.14

Table 4.2-1: Number of NUI students on board averaged over FY 1997, 1998, and 1999.

Effectiveness and Efficiency of Convening Schedules: As Figure 4.2-1 indicates, FY 2000 schedule is not effective at training the required number of sailors. To resolve this problem, it is helpful to examine an optimal solution from the Max-Out problem with a double number of convenings and an onboard capacity of 5,750 students. Table 4.2-2 lists the number of convenings with at least one student enrollment in an optimal solution to the Max-Out problem. Comparing the number of convenings from the Max-Out problem against those in FY 2000 schedule reveals that four courses, 619J, 621S, 622L, and 6666, have shortages of 50% or more. In total, the number of convenings used by the Max-Out problem is roughly the same as the one for FY 2000 schedule and the average difference in the number of convenings for each course is approximately 8%. Implicitly, the results in Table 4.2-2 are based on the assumption that there is no setback (see Subsection 2.3) and no over or underselling of training quotas. On the other hand, the table identifies courses with too few and too many convenings and is useful for making

scheduling adjustments.

CDP	Number of Convenings FY 2000	Max-Out	% Difference
2444	60	50	-16.67
2450	26	32	23.08
6070	31	31	0.00
617V	344	339	-1.45
618J	70	77	10.00
618N	113	113	0.00
618Z	82	64	-21.95
619G	38	36	-5.26
619J	**12**	**21**	**75.00**
621L	124	110	-11.29
621N	22	22	0.00
621S	**6**	**9**	**50.00**
621V	153	110	-28.10
622L	**74**	**113**	**52.70**
6400	28	31	10.71
6609	29	30	3.45
6611	43	47	9.30
6662	37	39	5.41
6665	21	16	-23.81
6666	**14**	**21**	**50.00**
6668	97	107	10.31
6741	48	36	-25.00
Total/Ave	1472	1454	7.56

Table 4.2-2: A comparison of two sets of convenings, one is from FY 2000 and the other is from an optimal solution to the Max-Out problem. Note that 619J, 621S, 622L, and 6666, have shortages of 50% or more.

Solutions to the Min-AI problem are useful in evaluating the efficiency of convening schedules. In particular, the optimal objective value of the problem provides the amount of 'between courses' AI time inherent in a set of convening and graduation dates. A better scheduling of these dates may lower the 'between courses' AI time. Table 4.2-3 summarizes the results from solving the Min-AI time with an onboard capacity of 5,750 students and a double number of FY 2000 convenings.

	Input	AI Time (in days) MAX	AVE	Training Time (in days) AVE.	NTMPS	% Diff.
AN	4363			20.18	19	6.21%
DC	541	3	2.82	77.55	73	6.23%
EM	775	2	2.57	139.86	126	11.00%
EN	898	6	4.97	111.68	116	-3.72%
ET(Comm)	1125	5	2.05	253.01	234	8.12%
ET(Radar)	750	5	2.48	249.37	227	9.85%
FC	1481	5	2.11	232.59	213	9.20%
FN	2688			19.81	19	4.26%
GM	735			118.07	164	-28.01%
GSE-pipe 1	258	5	5.67	187.77	178	5.49%
GSE-pipe 2	111	1	1	114.16	100	14.16%
GSM	476	4	3	99.59	97	2.67%
HT	510	3	3	74.44	73	1.97%
IC	654	4	3.94	150.38	136	10.57%
MM	1152	6	3.75	74.58	69	8.09%
MR	198	4	1.58	103.39	94	9.99%
QM	303			42.3	40	5.75%
RM	2654			105.18	96	9.56%
SM	408			33.86	33	2.61%
SN	4363			12.65	12	5.42%
TM	241			73.37	68	7.90%
Tot/Ave	24684		27014	82.03		

Table 4.2-3: Results from solving the Min-AI problem with an onboard capacity of 5,750 students and twice the number of FY 2000 convenings. Ratings requiring only one course (e.g., QM, RM, and SM) have no 'between courses' AI time. NTMPS training times are simply the sum of the lengths of the courses in the pipeline from NTMPS data. Since actual course lengths vary depending on the convening dates, actual training times may be more or less than NTMPS times.

When compared to training times obtained by adding together the appropriate course lengths in NTMPS (or NTMPS training times), the average training times from the Min-AI problem may be more or less because the actual course lengths vary depending on the convening dates. In addition, the training time from Min-AI includes 'between courses' AI time as well as the II time due to weekends and holidays. Thus, the difference between the average and NTMPS times is typically more than the average 'between courses' AI time for each rating. For example, the 'between courses' AI time for 'GSE-pipe 2' is approximately 1 day. However, the difference between the average and NTMPS training times is approximately 14 days. This implies that the extra 13 days may be due to weekend and holiday interruptions. On the other hand, observe that, using

the (optimal) allocation of students to courses from the Min-AI problem, it is possible to have an average training time (see, the training time for rating GM in Table 4.2-3) that is 28% less than the NTMPS training time.

Also, observe that ratings that require only one training course (e.g., QM, RM, and SM) do not have 'between courses' AI time. Moreover, the last row in Table 4.2-3 indicates that inherent in FY2000 schedule with a double number of convenings is the 'between courses' AI time of 27,014 days. Using a conservative cost of $25,000 per man-year (see, e.g., Belcher et al [1999]) and a 365-day man-year, 27,014 days translate to roughly $1.8 million. (Based on a 260-day man-year (or 52×5), the cost is $2.6 million instead.) However, it should be noted that the $1.8 million figure is based on doubling the number of convenings without changing the dates. Therefore, a better schedule may yield a lower AI cost.

Setting Quotas: One of the assumptions in both Max-Out and Min-AI problems is that the student sailors can arrive at the training site exactly on the required convening date. To ensure that this assumption holds, or nearly so, in practice, results from the Min-AI problem need to be incorporated into the system that sets and manages the training quotas, e.g., the Navy Training Reservation System (NTRS). Table 4.2-4 provides a set of quotas generated from an optimal solution to the Min-AI problem with a double number of FY 2000 convenings and an onboard capacity of 5,750 students.

Assuming that there is no under or overselling of quotas, the results from the Min-AI problem also produce profiles of student on board and under instruction at the training site as shown in Figure 4.2-2. The shape of the profiles in this figure generally depends on the scheduling of convening and graduation dates as well as the onboard capacity. A better schedule may yield a profile requiring less onboard capacity. Simply adding an extra class to each FY 2000 convening date does not generally yield desirable profiles.

	617V			618J			6070		
	Quota	Conv.	Grad.	Quota	Conv.	Grad.	Quota	Conv.	Grad.
1	10	7-Oct-99	28-Oct-99	10	29-Oct-99	7-Feb-00	10	8-Feb-00	8-Mar-00
2	50	26-Oct-99	16-Nov-99	50	17-Nov-99	24-Feb-00	50	25-Feb-00	23-Mar-00
3	50	15-Nov-99	7-Dec-99	50	8-Dec-99	15-Mar-00	50	17-Mar-00	13-Apr-00
4	50	22-Nov-99	14-Dec-99	50	15-Dec-99	22-Mar-00	50	24-Mar-00	20-Apr-00
5	50	14-Dec-99	11-Jan-00	50	12-Jan-00	5-Apr-00	50	6-Apr-00	3-May-00
6	50	5-Jan-00	26-Jan-00	50	27-Jan-00	19-Apr-00	50	21-Apr-00	18-May-00
7	50	19-Jan-00	8-Feb-00	50	10-Feb-00	3-May-00	50	4-May-00	1-Jun-00
8	50	3-Feb-00	24-Feb-00	50	25-Feb-00	17-May-00	50	18-May-00	15-Jun-00
9	50	17-Feb-00	9-Mar-00	50	10-Mar-00	1-Jun-00	50	2-Jun-00	29-Jun-00
10	50	24-Feb-00	15-Mar-00	50	17-Mar-00	8-Jun-00	50	9-Jun-00	10-Jul-00
11	50	3-Mar-00	23-Mar-00	50	24-Mar-00	15-Jun-00	50	16-Jun-00	17-Jul-00
12	50	17-Mar-00	6-Apr-00	50	7-Apr-00	29-Jun-00	50	30-Jun-00	31-Jul-00
13	50	19-Jun-00	10-Jul-00	50	11-Jul-00	2-Oct-00	50	4-Oct-00	2-Nov-00
14	50	26-Jun-00	17-Jul-00	50	18-Jul-00	10-Oct-00	50	11-Oct-00	8-Nov-00
15	50	18-Jul-00	7-Aug-00	50	8-Aug-00	31-Oct-00	50	2-Nov-00	2-Dec-00
16	10	8-Aug-00	28-Aug-00	10	29-Aug-00	22-Nov-00	10	23-Nov-00	16-Dec-00
17	45	21-Aug-00	11-Sep-00	45	13-Sep-00	7-Dec-00	45	9-Dec-00	23-Jan-01
18	10	21-Sep-00	12-Oct-00	10	13-Oct-00	23-Jan-01	10	24-Jan-01	22-Feb-01

Table 4.2-4: An optimal solution to the Min-AI problem provides quotas for Electrician's Mate rating. These quotas specify the number of training seats to be reserved for student sailors with EM rating.

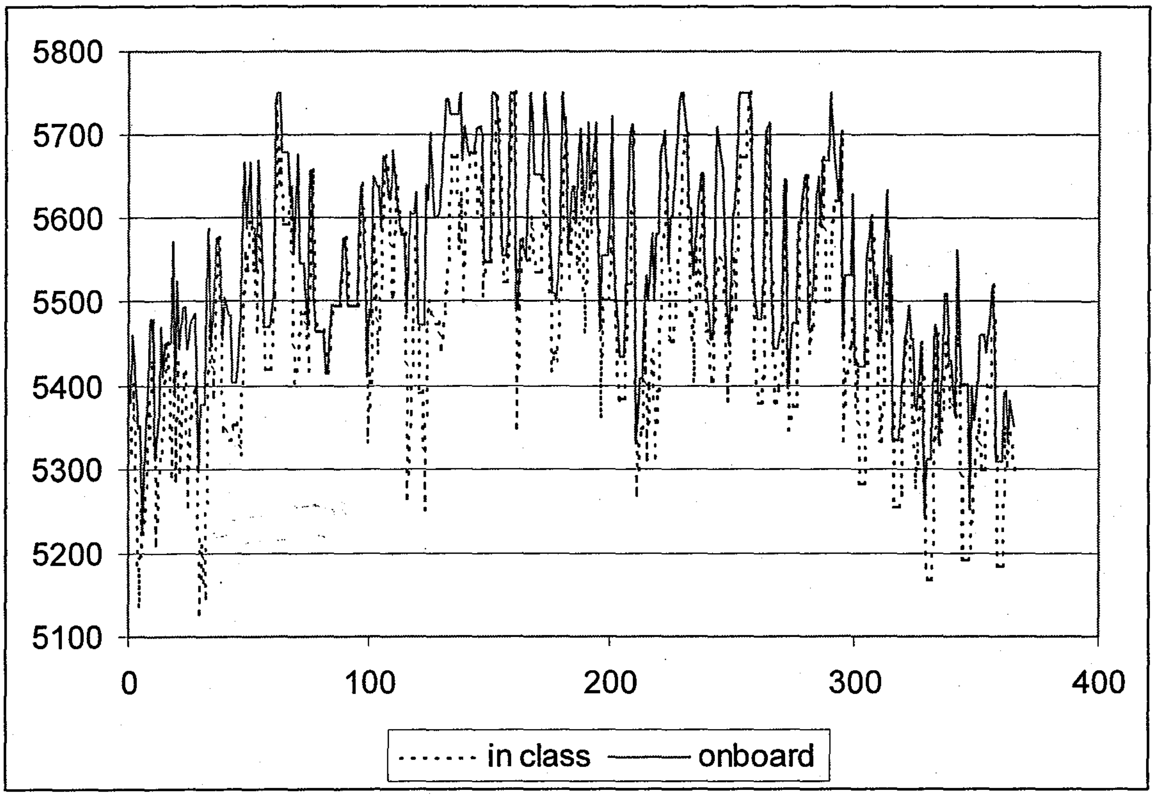

Figure 4.2-2: Profiles of students on board and students under instruction from an optimal solution to the Min-AI problem with an onboard capacity of 5750 students and a double number of FY 2000 convenings.

5. CONCLUSIONS

This report describes two optimization problems–the Maximum Output and Minimum 'between courses' AI time problems. Using the data for the Service School Command at Great Lakes, optimal solutions for these two problems suggest that the onboard capacity at the Command should be between 7,361 and 8,254 students and there are 27,041 days of 'between courses' AI time inherent in the FY 2000 course schedule. In addition, solutions to the Minimum 'between courses' AI time problems also provide information useful in setting and managing training quotas.

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